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STRONG FIELD FOCUSING FOR SIGNAL GENERATING IMAGE TUBES

by Jay Burns

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UNIVERSITY OF CHICAGO
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ABSTRACT

The application of strong magnetic focusing to signal generating image tubes is discussed, and its advantages are pointed out. A simple tube suitable for strong focusing is described. Storage target and image intensifier gain requirements to overcome video amplifier noise are discussed. It is concluded that strong focused signal generating tubes are practical and can offer substantial improvements in performance over present tubes in astronomical applications.

In a recent report[1] the principles and advantages of strong magnetic focusing for image converters of the non-signal generating type were presented. The present report extends that treatment to signal generating image tubes and gives a brief analysis of the sort of performance that may be achieved in such tubes using strong focusing.

For the sake of concreteness we shall adopt a model signal generating image tube of the form shown in Fig. 1. In this tube light incident on the semitransparent photocathode from the left produces photoelectrons that are accelerated and focused upon the storage target at the center, giving rise to a surface potential pattern on the right surface of the target which is subsequently read off by a scanning beam of electrons generated at the right hand photocathode by a flying spot of light from the cathode ray tube at the far right, this CRT being out of the magnetic field which focuses the image section and scanning beam of the image tube. Such a device represents only one of several configurations that can be devised to accomplish the signal integration and read-out operations in a signal generating tube employing the strong focusing principle. Since this particular model shows all of the features we wish to discuss, it is convenient to confine the analysis to it alone.

The term strong focusing in the present discussion means the use of an axial magnetic field of sufficient strength to cause electrons moving

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1. Jay Burns, "Strong Magnetic Focusing for Electronographic Image Tubes", LAS-TR-226-5, March 1964.

from the signal photocathode to the storage target, or between the reading beam photocathode and the storage target, to move in tight helical paths spiralling about a magnetic field line, the resolution being determined by the radii of these helical paths. As shown in Ref. 1, the diameter, δ, of a resolution element is approximately half the radius of such a helix and is numerically given by the relation

$$\delta \approx \frac{17 \sqrt{V_{max}}}{B} \quad \text{millimeters} \tag{1}$$

where B is the axial field in gauss, V_{max} is the maximum initial electron energy in electron volts. It is assumed that magnetic and electric accelerating fields are parallel; deviations from exact parallelism lead to small second order lateral displacements of the electrons from their initial magnetic field lines and will be discussed in Appendix A.

It is convenient to visualize the electrons as being effectively confined by the strong field to small imaginary tubes extending along the magnetic lines of force from a photocathode to target. These tubes are of diameter, δ, equal to the size of a resolution element, and the electrons within a tube are isolated for practical purposes from electrons of neighboring resolution elements. Moreover, the "resolution channels" formed by such imaginary tubes are quite rigid against lateral displacements caused by small perturbing electric or magnetic fields with the result that strong focusing greatly reduces distortion of the image by such perturbing fields. With strong magnetic fields there is no focusing of the electron image in the usual sense but rather a rigid collimation of the electrons from each resolution element of the photocathode; therefore the strength of the electric field that accelerates the electrons from the cathode plays no role in determining the position of a focal plane, nor is there any exact relation between electric and magnetic field strengths that must be maintained to focus the tube. The velocity spread of the photoelectrons plays only a minor role in determining resolution in strong focused tubes in contrast with tubes focused by conventional weak fields of the order of a few hundred gauss.

The principal problem in design of a strong focused, signal generating image tube arises from the very lateral rigidity of the electrons which constitutes its chief virtue. This rigidity prevents one from using a reading beam generated by an electron gun because the beam cannot be deflected to scan the storage target. Instead of a point source reading beam from an electron gun, it is necessary to use an extended source such as the photocathode shown at the right end of the tube in Fig. 1 and to produce the reading beam by illuminating the reading beam cathode with a fine spot of light that is moved about to provide scanning. The reading electron beam at any point travels in a tube of magnetic confinement between cathode and target exactly as the original photoelectrons did, and if the light spot is small enough, the reading and writing steps will both have essentially the same resolution given by Eq. 1.

Four important advantages result from reading the target in this way: (a) there is no redistribution of reading beam electrons around the bright regions of the image to contribute the characteristic highlight halo of conventionally focused tubes, (b) there is no appreciable lateral bending of the reading beam into sharply defined highlight areas from adjacent dark regions, which gives rise to the common "black border effect", (c) since the reading beam electrons have a Maxwellian energy tail appropriate to a very low temperature emitter, namely, to the reading beam photocathode which can be cooled to make thermionic emission extremely small, there is for all practical purposes a sharp upper limit to electron velocities in the reading beam that facilitates resetting the target surface potential to a precise value after the image is read, and, finally, (d) the strong confinement of electrons by the field permits a high degree of modulation of the reading beam in the process of recharging the target as the image potential pattern is being read, and high modulation improves the signal-to-noise ratio.

Unfortunately the advantages just mentioned are not obtained without penalty. The means described for reading the stored image does not lend itself to amplification of the returned reading beam with an electron multiplier. Instead the video signal is taken directly from a conductive coating on the left side of the target or from the reading beam photocathode itself depending upon the signal polarity desired. If noise in the video amplifier is to be negligible, then some gain must be obtained in the tube itself by a process such as secondary electron multiplication which does not appreciably degrade the signal-to-noise ratio. Such multiplication can be obtained from transmission secondary emission through targets covered with low density KCl "smoke", e.g., the so-called SEC targets[(2)], the letters standing for secondary electron conductivity. Properly prepared and used, these SEC targets give stable gains in the range 40-60, and in applications that permit the picture to be read out slowly at a slow scanning rate, the video bandwidth can be reduced to optimize the signal-to-noise ratio with respect to amplifier noise[(3)] and under certain conditions (Appendix B) the SEC target alone can provide enough gain to overcome amplifier noise. Under these conditions,

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2. G. W. Goetze, "Advances in Electronics and Electron Physics", L. Marton, Ed., Vol. XVI, p. 145, Academic Press, N. Y. (1962).

3. R. Thiele, "Adv. in Electronics and Electron Phys." Vol. XII, Academic Press, N. Y. p. 277 (1960).

the limiting noise in the picture can be reduced to little more than the fundamental shot noise in the original photoelectric image which represents the ultimate performance possible for a given photocathode quantum efficiency. Therefore, slow readout plus the SEC target plus in many cases some added image intensifications between photocathode and storage target are essential to realize the full low light level performance of the strong focused tube. The relation between frame time, number of lines per picture, and internal gain required for a photocurrent noise limited tube is given in Appendix B where it is shown that a tube having a resolution of 50-100 line pairs/mm operating into a video amplifier with an input capacitance of ~ 5 $\mu\mu$f needs internal gain of $\geq 10^4$ if the load resistor is at room temperature and a gain of ≥ 135 for the load resistor at liquid helium temperature (4.2°K). The latter gain can be approached within about a factor 2 by present SEC targets, but the former value is unrealizable with the SEC target alone.

Fortunately, it is not necessary to develop all of the gain in the target itself. Part or most of it may be obtained by intensifying the photoelectric image before it reaches the storage target. Either the cascade photocathode-phosphor image converter or the transmission secondary emission (TSE) intensifier can be used for this purpose with the intensifier being incorporated into the signal generating tube between photocathode and SEC storage target. The TSE intensifier would seem to be particularly well suited to use in a strong focused tube because the interstage voltages in this intensifier are low enough so the dynodes may be spaced fairly close together making the tube more compact, and compactness is of some practical importance in keeping down the cost of the associated superconducting solenoid and cryostat. A total gain of ~ 200 is all that is required of the intensifier if it works into an SEC target. Since gains per stage of 5-6 can be obtained in the TSE intensifier, three or four stages would suffice. With strong focusing the resolution loss in the TSE intensifier would be negligible.

The preceding discussion is based upon a target storage capacity of $\sim 10^5$ electrons per resolution element to which the picture highlight elements would be charged. If an intensifier is incorporated into the tube, it is easily possible to achieve more gain than the minimum needed to raise the signal above amplifier noise. The extra gain serves the useful purposes of reducing the integration time required to get a satisfactory image at a given light level provided one does not use more gain than is needed just to detect the arrival of an individual photon. More gain than this wastes storage capacity of the target and reduces the dynamic range of light intensities that can be recorded before the target saturates. The maximum useful gain for a target with capacity of 10^5 electrons per resolution element capable of reproducing a 100:1 dynamic range is given by the expression $.01n_s = g\gamma$ (see Appendix B for notation). With n_s, the storage capacity, equal to 10^5 and a quantum efficiency $\gamma = 0.1$ the maximum value of g is 10^4 which is the same as the minimum required to overcome amplifier noise. (It should be mentioned that g here includes both intensifier and target gains). With a larger storage capacity or a lower quantum efficiency photocathode somewhat higher gan could be put to good use. In the above example, $g = 10^4$ and $\gamma = 0.1$ would deposit 10^3 charges on the storage target, a quantity of charge just observable above amplifier noise (Appendix B) under typical conditions.

The present remarks may be summarized by saying that a number of the virtues of strong magnetic focusing as applied to signal generating image tubes have been cited and one example of such a tube has been described. Analysis of target and/or associated image intensifier gain requirements to overcome video amplifier noise shows that either the input load resistor must be cooled to very low temperatures or image intensification must be employed between photocathode and target. The overall performance of such a tube is expected to exceed that available from present tubes by a substantial margin largely because of the favorable electron optical properties of the strong magnetic focusing. Strong focusing serves principally to reduce the common electron optical aberrations and distortions to negligible levels. Since it also eliminates electron redistribution during readout, point images such as stellar images no longer grow in size with exposure, and as a result the amplitude of the video signal for such an object is proportional to its brightness which is not the case in a conventional signal generating tube like the image orthicon. Thus quantitative photometric data can be obtained from pulse height measurements on the video signal in a strong focused tube which is a great advantage in many kinds of astronomical work, particularly where the output signal is meant to be processed by a computer.

APPENDIX A

Image Perturbations Caused by Weak Electric and Magnetic Fields

Consider the motion of an electron in parallel electric and magnetic fields shown in Fig. 2. The motion in a pure magnetic field is a circle of radius $R = mcv/eB$ in a plane normal to the magnetic field lines (m is electron mass, v its velocity in the plane of the orbit, e and c are the electronic charge and speed of light respectively, and B is the field strength). If an electric field accelerates the electron along the x-axis in Fig. 2, the motion will be a helix of radius R with increasing pitch along x, and the trajectory will be as shown in the figure.

If the electron moves in perpendicular electric and magnetic fields as shown in Fig. 3 the motion follows the cycloidal path shown provided the electron is initially at rest. The amplitude of the cycloid is given by the relation

$$A = 11.4 \frac{E}{B^2} \quad \text{centimeters} \qquad \text{(A-1)}$$

and its period along the x-axis by

$$L = \pi A \qquad \text{(A-2)}$$

where E is the electric field in volts/cm and B is the magnetic field in gauss.

Consider first the case in which a small perturbing magnetic field of strength B_1 exists normal to the axial magnetic and electric fields B_o and E. Combining B_o and B_1 vectorially leads to a new resultant field B' which defines a new magnetic axis displaced with respect to the old axis by $\theta = \tan^{-1}(B_1/B_o)$. Now electrons will spiral about the new field lines B' and will see a perturbing electric field normal to B', this perturbing electric field being the component of the original E_o perpendicular to B'. The perturbing electric field component will therefore be $E_o \sin\theta$. Since the perturbation is small $\sin\theta \approx \theta \approx B_1/B_o$ and

$$E_1 = E_o B_1/B_o \tag{A-3}$$

Therefore, the electrons will spiral about a line stretched into the shape of a cycloid (Fig. 4) of amplitude

$$A = 11.4 \frac{E_1}{B'^2} \approx 11.4 \frac{E_o B_1}{B_o^3} \text{ centimeters} \tag{A-4}$$

Typical values of E_o and B_o are 10^3 volts/cm and 10^4 gauss respectively so $A \approx 10^{-8} B_1$ cm which is quite negligible for any B_1 small enough to be treated as a perturbation.

Consider next a small perturbing electric field, E_1, normal to the axis of B_o, E_o. Again the electron path will be a spiral about a line stretched into cycloidal shape and the amplitude of the cycloid is

$$A = 11.4 \frac{E_1}{B_o^2} \quad \text{centimeters} \tag{A-5}$$

For $B_o = 10^4$ gauss, $A \approx 10^{-7} E_1$ cm, and this is also negligible for any weak perturbing field, E_1.

The conclusion is that in strong focusing with axial fields of the order of a few kilogauss the electrons are not displaced laterally by perturbing electric or magnetic fields.

APPENDIX B

Target Gain Needed to Overcome Video Amplifier Noise

Consider a square image tube storage target having N TV lines, or $\frac{1}{4}N^2$ picture elements (since there are 2 TV lines to a strip one resolution element wide due to the convention for counting TV lines). If this picture is read off in τ seconds, the highest frequency in the video signal will be

$$\nu_{max} = \frac{1}{2}\left(\frac{N^2}{4\tau}\right) = \frac{N^2}{8\tau} \tag{B-1}$$

and this will be the bandwidth required for the video amplifier. The reading beam will dwell for a time $t_o = (2\nu)^{-1}$ on a single picture element.

Let n_o light quanta from a stellar point image fall on a resolution element of size δ during the image integration time. If the average quantum efficiency of the photocathode is γ and the average internal multiplicative electron gain of the storage target is g, then each incident photon will produce on the average γg stored electrons on the target. If n_s electrons are stored per resolution element of the target

$$n_o = \frac{n_s}{g\gamma} \tag{B-2}$$

and if the reading beam can read off a fraction, f, of this stored charge in one scan, then the signal current from the resolution element being considered will be

$$i_s = \frac{efn_s}{t_o} = \frac{efn_sN^2}{4\tau} = \frac{efg\gamma n_oN^2}{4\tau} \tag{B-3}$$

where e is electronic charge, 1.6×10^{-19} coulombs, and i_s is the signal current in amperes from the resolution element under consideration.

The mean square noise in the signal current, i_s, taking into account variances in ν and g, may be shown[4] to be

$$\overline{\Delta i_s^2} = e^2 fg\gamma n_o \left(\frac{N^2}{4\tau}\right)^2 (g\gamma + g + 1) \tag{B-4}$$

If the voltage input to the video amplifier is developed across an input resistor R at a temperature T, the noise generated in this resistor is

$$\overline{\Delta i_R^2} = \frac{4kT\nu}{R} \tag{B-5}$$

and if the equivalent noise resistance of the first amplifier tube is R_e shunted by stray capacitance C, the noise from this source will be

$$\overline{\Delta i_A^2} = \frac{4kT}{R^2} R_e \nu \left(1 + \frac{4\pi^2}{3} R^2 C^2 \nu^2\right) \tag{B-6}$$

Note that $RC\nu \lesssim 1$ since the bandwidth cannot appreciably exceed the frequency at which the stray capitance begins to shunt the signal current around the load resistance R.

4. E. F. DeHaan, "Advances in Electronics and Electron Physics", Vol. XII, L. Marton, Ed., Academic Press, N. Y., 1960, p. 291.

If the performance of the system is not to be degraded by the noise in the load resistor and video amplifier, the gain, g, must be large enough so

$$\Delta i_s^{\,2} \gg \overline{\Delta i_R^{\,2}} + \overline{\Delta i_A^{\,2}} \tag{B-7}$$

Applying this criterion and rearranging with the help of (B-1) and (B-2) we have

$$g \gg \frac{kT}{e^2 R f n_s \nu(\gamma + 1)} \left(1 + \frac{R_e}{R} + \frac{4\pi^2}{3} R R_e C^2 \nu^2 \right) - \frac{1}{\gamma + 1} \tag{B-8}$$

This expression can be simplified considerably by noting that: (a) for photo-emitters $\gamma \ll 1$, (b) a video amplifier would be chosen in which $R_e \ll R$, and (c) R would be chosen so $2\pi RC\nu \approx 1$. Under these conditions a sufficiently good criterion for minimum SEC target gain becomes simply

$$g \gtrsim \frac{2\,kT}{e^2 R \nu f n_s} \tag{B-9}$$

This expression may be put into a still more convenient form by noting that if $2\pi RC\nu = 1$, the factor $2\,kT/e^2R\nu = 4\pi kTC/e^2$. The latter quantity has a value ~ 2×10^{18} C at room temperature or approximately 10^7 for a typical $C \approx 5$ $\mu\mu$f. Therefore

$$g \gtrsim \frac{10^7}{f n_s} \tag{B-10}$$

for a load resistor at room temperature.

The storage capacity of an SEC target is reported by Boerio and Goetz[5] to be ~ 3×10^{10} electrons per cm^2 or between 3×10^4 and 10^5 electrons per resolution element (δ = .01 to .02 mm). A minimum value of $n_s \approx 10^3$ electrons would yield 1-3% photometric accuracy. If $f \approx 1$, as it can be in a strong focused tube, the minimum target gain is $g \approx 10^4$ which is more than two orders of magnitube above SEC target gains. It is possible that the SEC target storage capacity could be further increased, for the value quoted by Boerio and Goetze does not produce an internal electric field in the KCl layer approaching the breakdown value. Another approach would be to cool R to liquid helium temperature, a feasible step with a strong focused tube employing a superconducting solenoid. The corresponding reduction in g would be roughly a factor of 75 which is the reduction in T. Therefore, a g of only ~ 135 would be needed, and this is within a factor 2 of commonly obtained gains in SEC targets. Under certain conditions of surface potential much higher values of g can be obtained[5], but under these conditions g varies during the signal integration period and this introduces non-linearity into the response of the tube, ruling out quantitative photometry. The effect of high magnetic fields on g and on storage capacity of SEC targets is unknown and needs to be investigated before any strong focused tube development is undertaken.

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5. A. H. Boerio and G. W. Goetze, Westinghouse Scientific Paper 62-112-252-P3, Westinghouse Research Laboratories, Pittsburgh, Pennsylvania.

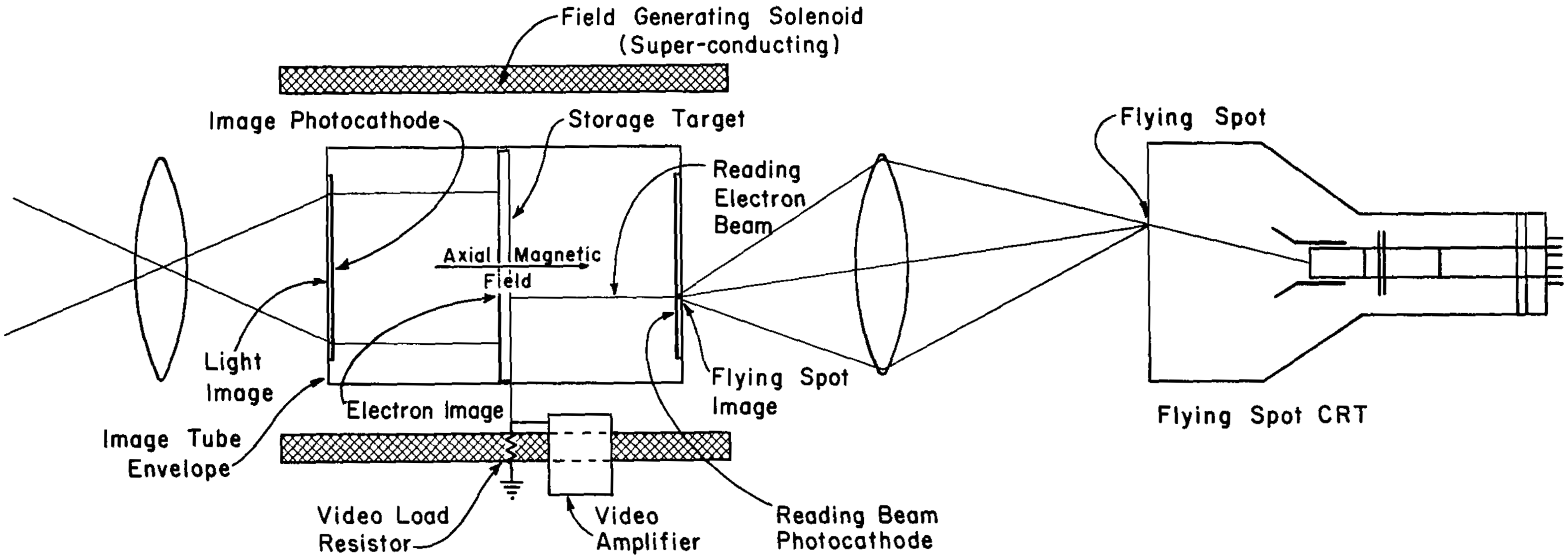

Fig. 1. Sketch of a typical arrangement for a strong field focused signal generating image tube with flying spot generated readout. The tube is not to scale. In practice it would be located deep within a helium cryostat (not shown) designed with both ends open for the light to have access. Only the superconducting coil is at liquid He temperature; the tube temperature can be any desired value.

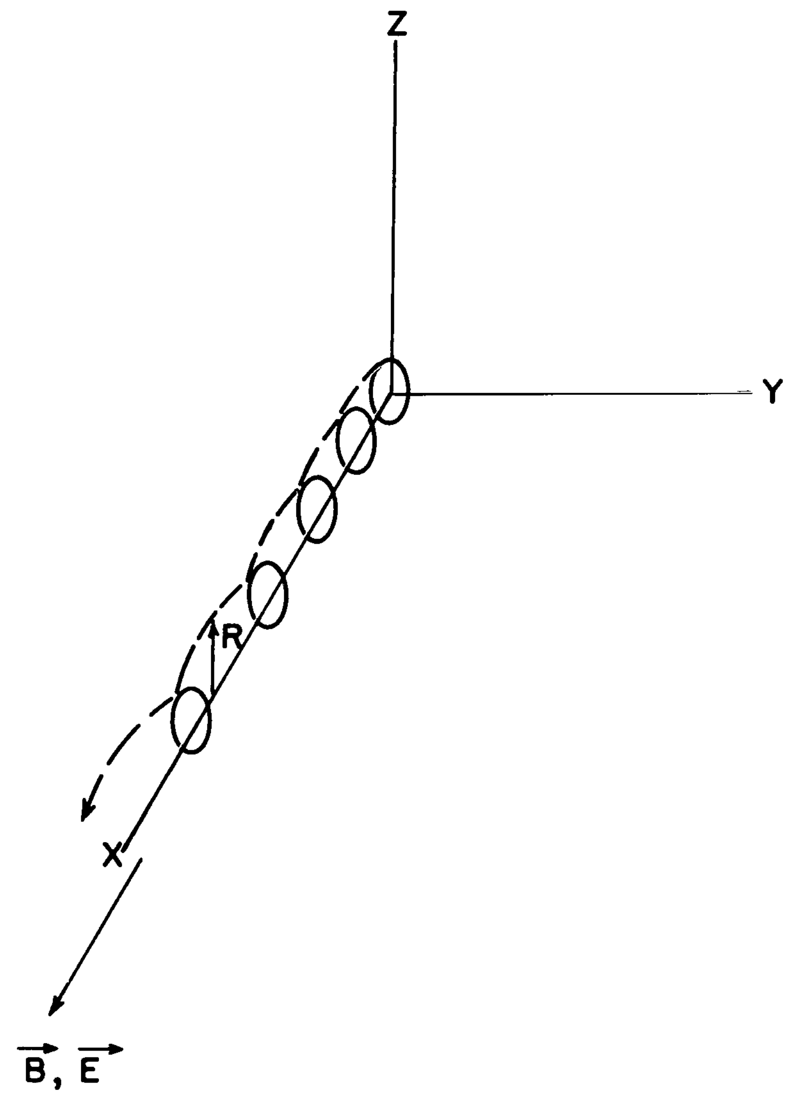

Fig. 2. Trajectory of a charged particle in parallel electric and magnetic fields.

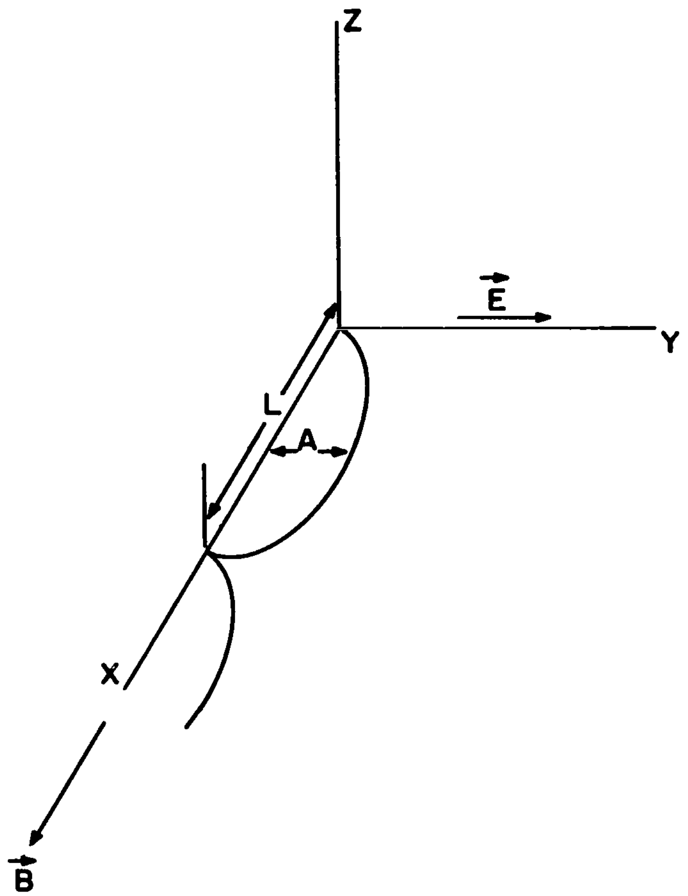

Fig. 3. Trajectory of charged particle in crossed electric and magnetic fields.

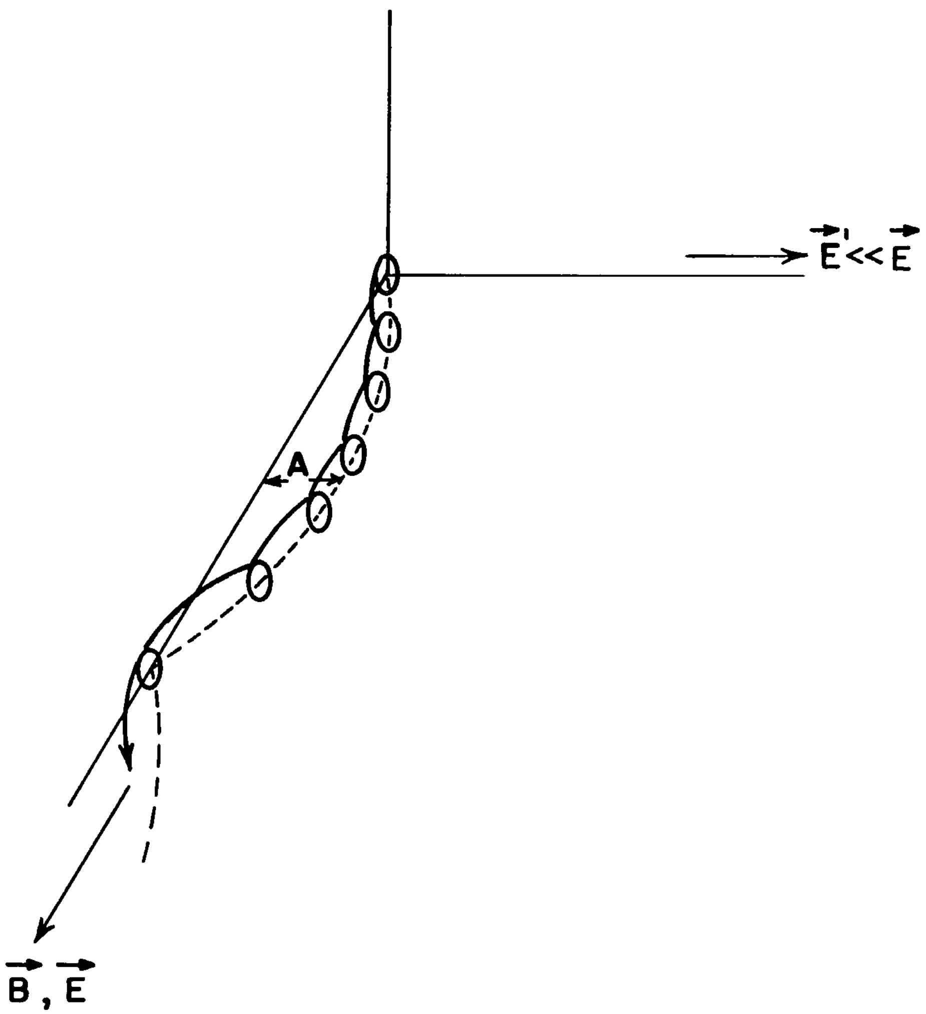

Fig. 4. Trajectory of charged particle in parallel electric and magnetic fields with perturbing transverse electric field.

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